ANALYSIS OF THE TURBULENT WIND ABOVE AND WITHIN A FIR FOREST

Ana Scarabino, Ulfilas Boldes, Jorge Colman and Julio Marañón di Leo.

Laboratorio de Capa Límite y Fluidodinámica Ambiental
Facultad de Ingeniería, Universidad Nacional de La Plata
Calle 116 e/ 47 y 48, 1900 La Plata, Argentina.

ABSTRACT

In this work wind data from the measuring tower in the Solling fir forest at Goettingen, Germany, are processed and analyzed. Wind records are supplied by the Institute of Bioclimatology at the Georg Augustus University. An attempt is made to identify some of the vortical structures at the upper shear layer, and to study their penetration into the lower atmosphere within the forest and the interaction with the low velocity flow at this region. Analysis of anemometrical data suggests two types of phenomena coexisting in the upper mixing layer region of the flow: large-scale roughness-type independent phenomena, and structures of frequent penetration with smaller length scales, related to vertical transport processes.

Key Words: wind in forests, turbulence, shear layer, coherent structures.

I. INTRODUCTION

On the upper region of the forest, a shear layer develops, connecting a relative high mean velocity upper region, in which the more energetic wake processes occur, with the slower bleed flow at the lower levels.

Turbulent shear flows are very sensitive to small changes in initial or boundary conditions ([1], [2], [3]). The upper mixing layer region constitutes the main source of turbulent kinetic energy in forest aerodynamics. The highly turbulent mixing layer imposes decisive upper boundary conditions to the flow within the forest. This shear layer, at which the prevailing non-linear transfer processes occur, is characterized by a large range of time scales. Raupach et al. [4] proved that canopy air motion is far from random, with major contributions to turbulent motions arising from coherent eddies. Gaining a good knowledge of air motion in forest is a necessary first step towards a better understanding of static and dynamic wind loads, spread of seeds, pollens and spores, dispersion of pesticides, deposition of air pollutants, exchange of greenhouse gases, etc. [5]. In observations of Gao et al. [6], identified structures were responsible for more than 75% of the total fluxes of heat and momentum at mid canopy heights

Approximately below half the height of the canopy, the more we descend the smaller becomes the mean velocity with more frequent occurrence of periods of very slow velocities. These middle and low height regions of moderate mean velocity are intermittently penetrated by relatively large fluid structures that are mainly responsible for the transport phenomena within these canopy heights. In what follows we try to describe aspects of these structures.

II. METHODOLOGY

In the forest of Solling, Germany, 3-D instantaneous velocity components were acquired at a sample rate of 10 Hz, in 15-min. records, with ultrasonic anemometers METEK USAT – 1, installed by the Institute of Bioclimatology. The results showed in this work correspond to simultaneous measurements at heights of 39 and 2 m. (z/H = 1.3 and 0.07 respectively). The forest mean height, H was aprox. 30 meters, hence the first records represent wind velocities above the trees, in the forest shear layer, and the second are relatively close to the ground, well below the treetops. The data for the presented analysis were acquired between 1.30 and 1.45 pm, thus an unstable atmosphere is expected above the forest.

Longitudinal, lateral and vertical velocity components were processed to obtain overall statistical parameters, quadrant analysis for the velocity fluctuations, auto- and cross correlations and wavelet maps

III. RESULTS AND DISCUSSION

Time-Velocity Graphs and Statistics. Figure 1 shows the temporal evolution of velocity fluctuations at both levels, and Table I summarizes the velocity statistics for both records. The behaviors of mean velocities, turbulence intensities and higher order moments matched the orders of magnitude for the mixing layer analogy proposed by Raupach [4]. The Reynolds stresses disappeared close to the ground, as they were expected to [5]. The signs of skewness for the longitudinal and vertical components at both levels were consistent with the q-hole analysis described in following paragraphs. The time-velocity graphs show merely by visual inspection some clear differences in the flow at the top and within the forest, and allow an intuitive detection of the downward penetration of some strong fluctuations from the shear layer.

Table 1. Velocity statistics

Z/H = 1.30		**Z/H = 0.07**	
$\overline{U} = 2.75\ m/s$	$\overline{W} = 0.00\ m/s$	$\overline{U} = 0.6\ m/s$	$\overline{W} = 0.01\ m/s$
$\sigma_u = 1.62\ m/s$	$\sigma_w = 0.87\ m/s$	$\sigma_u = 0.51\ m/s$	$\sigma_w = 0.13\ m/s$
$T_u = 0.59$	$T_w = 0.32$	$T_u = 0.85$	$T_w = 0.21$
$Sk_u = +0.37$	$Sk_w = -0.13$	$Sk_u = -0.41$	$Sk_w = +0.37$
$K_u = 2.54$	$K_w = 3.22$	$K_u = 3.91$	$K_w = 7.07$
$\overline{u'w'} = -0.73\ m^2/s^2$		$\overline{u'w'} = 0.003\ m^2/s^2$	

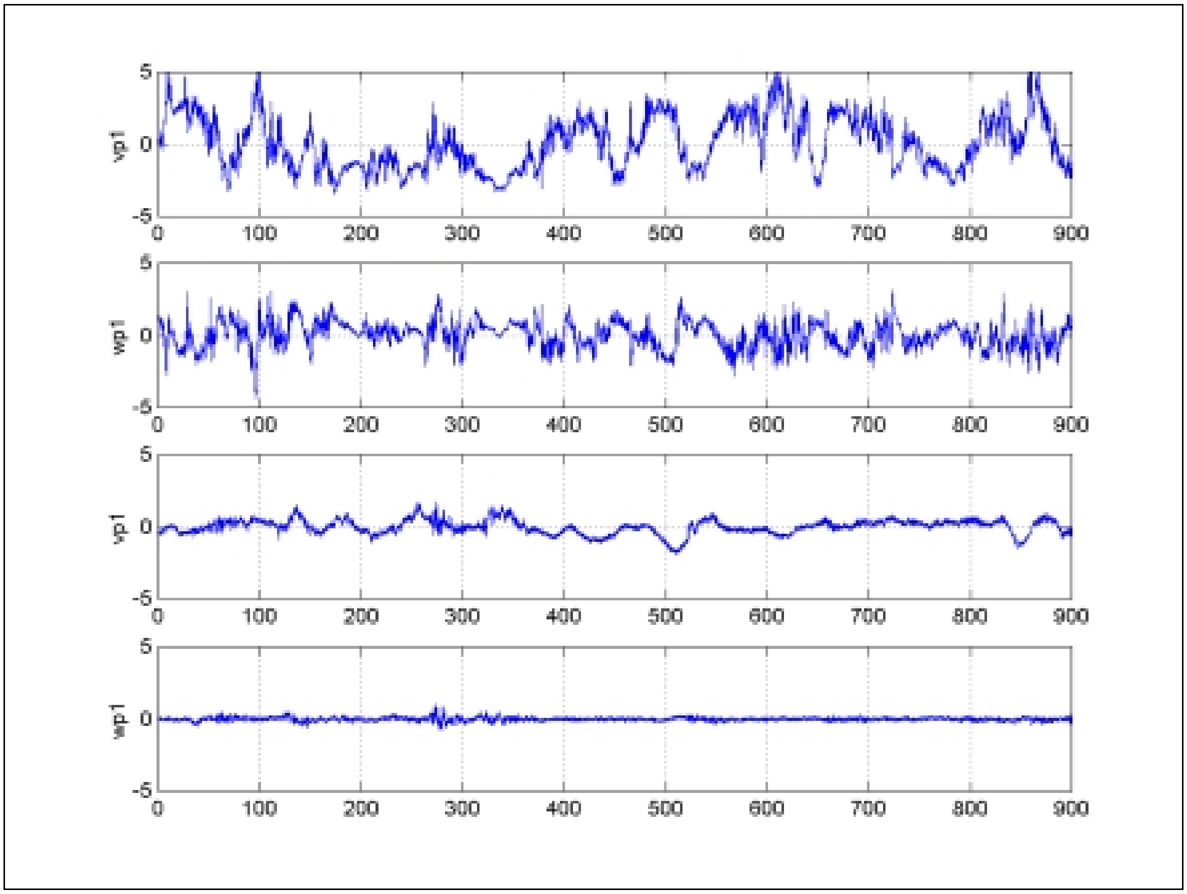

Fig. 1. Velocity fluctuations. Horizontal axis is time in s., velocities are in m/s

The structure of the velocity fluctuations is more evident in Fig. 2, which shows the temporal evolution of the instantaneous V' vector. The rotation of the upper V' projection onto the x-z plane suggested a Kelvin-Helmholz type instability. One can distinguish some structures that have an effect on the flow below, from others whose influence does not reach that level. With the addition of the lateral component, a picture arises of a longitudinal vortex embedded and modulated by the shear layer. As discussed by Raupach et al. [6] and Bergström and Högstrom [7], isolated roughness elements (trees in this case) create "horse-shoe vortices" that bend around the elements and extend far downstream, being lifted, oscillating and breaking in the turbulent flow. Also Shabaka et al [9] proposed different mechanisms for the generation of longitudinal vortices in shear flows, which can be acting in this case.

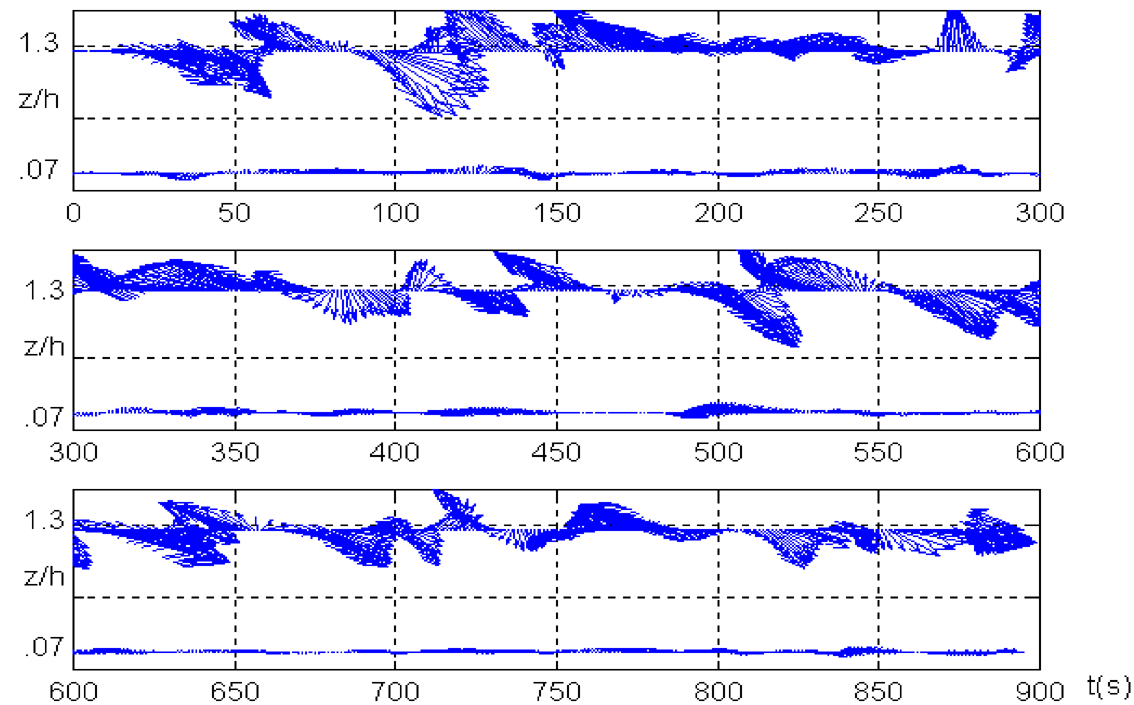

Fig. 2. Projection of velocity fluctuations on the x-z plane

Quadrant Analysis. Quadrant analysis of velocity fluctuations was performed in the vertical plane, parallel to the horizontal mean velocity, as it is customary in 2-dimensional boundary layers [10]. The results at the top shear layer showed a clear predominance of "sweep" (quadrant IV) and "ejection" or "burst" (quadrant II) events, which occurred during aprox. 80 % of the time of measurement, while at 2 m the four quadrants contributed approx. equally to the turbulent motion. (Table 2).

Table 2. Relative frequencies of simultaneous events at two heights

	QI - l	QII - l	QIII – l	QIV - l	Sum -u
QI – u	0.0469	0.0291	0.0145	0.019	0.1095
QII – u	0.1665	0.0682	0.0559	0.1006	0.3912
QIII – u	0.0402	0.0179	0.038	0.0235	0.1196
QIV – u	0.0391	0.0927	0.1486	0.0994	0.3798
Sum - l	0.2927	0.2079	0.257	0.2425	1

While the fraction of time was similar for contributions at the top level from the second and fourth quadrants, the quadrant-hole analysis, as described in [7], evidenced that the intensities of the Q IV fluctuations (positive longitudinal and negative vertical) were remarkably higher than those of Q II. The values and signs of skewness for z/H = 1.3 confirmed this asymmetry.

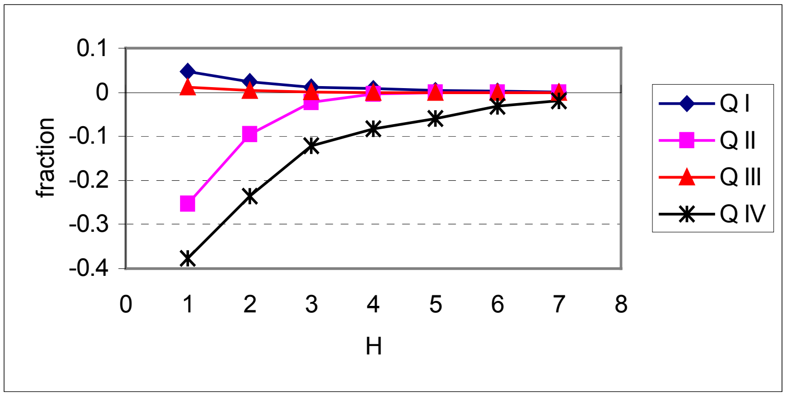

Fig. 3. Q-hole analysis.

Correlation Analysis. Table III shows cross correlations of longitudinal and vertical velocity components, in the same and in both height levels, computed over the 15 min. record and for t between 450 and 550 sec. The latter is an interval where the velocity graph indicated an alternating ejection-sweep-ejection event at the top shear layer, which penetrated into the lower layers of the forest atmosphere.

Table 3. Cross Correlations

	Whole Period	t = 450-550 s
C_{v1w1}	- 0.5449	- 0.7203
C_{v1v2}	- 0.3021	- 0.3751
C_{v1w2}	- 0.1245	- 0.2634
C_{w1v2}	+ 0.2344	+ 0.2380
C_{w1w2}	+ 0.1213	+ 0.2966
C_{v2w2}	- 0.0427	- 0.3183

While the global U-W correlation was relatively high at the shear layer, suggesting some organization in the flow, this feature was lost near the ground. However, correlations were appreciably higher when restricted to selected intervals, showing evidence of organized structures that sporadically penetrated the whole wind field.

Time correlation graphs were remarkably modulated, as were the velocity components (Fig. 4). An attempt to define a global time scale for the turbulence by integration of the autocorrelation function failed, because it depended strongly on the extent of the integration interval. Wavelet analysis provided in this case a better identification of time scales present in the field.

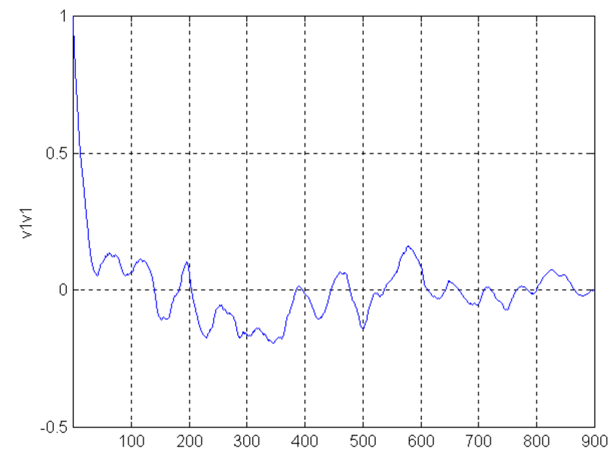

Fig. 4. Autocorrelation for the longitudinal component at z/H = 1.3

Wavelet Analysis. As Farge points out, it seems much better to decompose a turbulent field into such localized oscillations of finite energy as wavelets, rather than into space-filling trigonometric functions, which are not of finite energy [11]. For our analysis, the "Mexican hat" wavelet was used, which performs acceptably well for identification of local maxima at different scales [12]. Black lines show graphically the different time scales.

The scales and regular arrangement of the structures detected in our preliminary wavelet analysis agreed with the roughness-type independent periodic model proposed by Raupach [13]. According to his suggestion, in the inflection-point region above the forest, an intense inviscid Kelvin-Helmholz type instability develops, promoting rapidly growing transverse vorticity perturbations with a streamwise wavelength of the order of 8-10 H [14]. In the present evaluation case (H ≈ 30 m) we obtained an approximate wavelength of 300 m., consistent with the energetic time scales around 150 s.

Raupach in [4] states that turbulent length scale measurements show that eddies dominating turbulent transfer are of canopy scale (H), and therefore "coherent" (correlated) in this scale. The second energetic scale observable in the wavelet graphs was clearly that of 10-20 seconds, or, with frozen flow theory, around 1 – 1.5 H. This was also the most energetic scale for the vertical fluctuations at the shear layer, and of comparable intensity with the larger scale structures, in the longitudinal fluctuations at the lower flow.

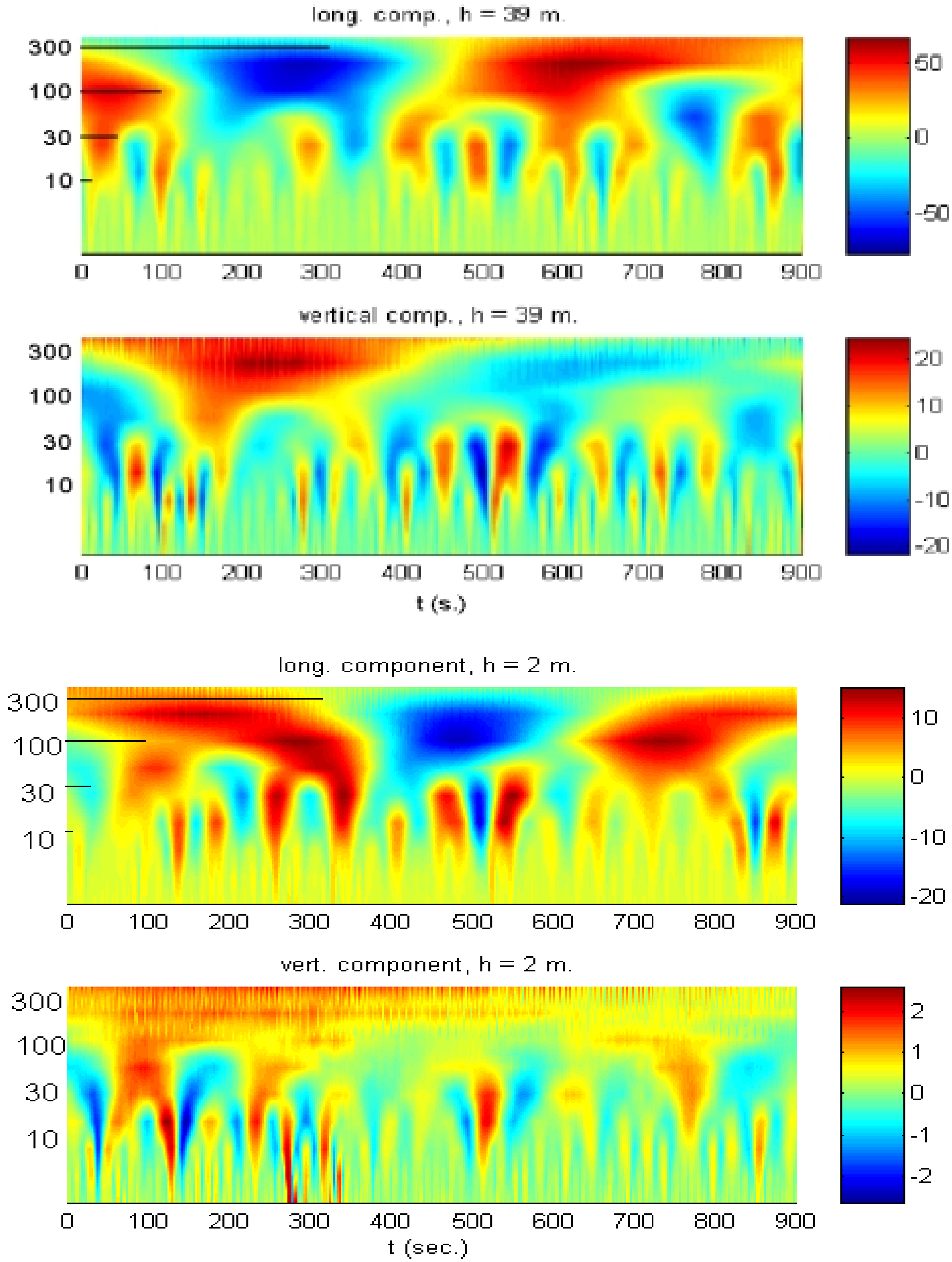

Fig. 5. Wavelet Graphs.

IV. CONCLUSIONS

The presented results suggest two types of phenomena coexisting in the upper mixing layer region:

1) *Large scale roughness-type independent phenomena* (Raupach), promoted by the unstable inflection-point mean velocity distribution, due to the bulk presence of the forest. Structures possibly modulated by Kelvin-Helmholz type instabilities penetrate intermittently the lower heights of the forest. Their mixing effect must be important due to their energy and scale, compared with the relatively calm forest atmosphere close to the ground.

2) *Structures of scale H, related to vertical transport processes*. These structures of very frequent downward penetration, are probably dependent of the characteristics of the forest canopy and are apparently of the same type as those reported in [4] .

The picture that emerges from these evaluations corresponds to a mixing layer in which the horizontal velocities are associated to prevailing large-scale structures with occasional intermittent events in which vertical momentum is injected into the lower canopy levels.

On the other hand, the mixing layer vertical velocities are related to frequent structures of scale H, that penetrate within the canopy and are detected in the horizontal velocity records at low heights.

A physically realistic numerical model of the transport processes in the forest region should consider these different scales of the flow.

We expect that future forest experiments with an adequate space distribution of anemometric probes will supply further data, which will provide improved information about the real shape of the structures within the forest canopy.

V. ACKNOWLEDGEMENTS

This work was carried out under a cooperation program between the Institute of Bioclimatology (Goettigen, Germany) and the Boundary Layer and Environmental Fluid Dynamics Laboratory (University of La Plata, Argentina).

VI. REFERENCES

[1] Oster D. Wygnanski I. and Fiedler H.E. (1977) Some preliminary observations on the effect of initial conditions on the structure of the two-dimensional turbulent mixing layer. *Turbulence in Internal Flows*, edited by S.N.B. Murthy, pp. 67-87, Hemisphere, Washington, 1977.

[2] Cantwel B. J. (1981) Organized motion in turbulent flow. *Annual Review of Fluid Mechanics* Vol. 13, 457-515.

[3] Oster D. and Wygnanski I. (1982) The forced mixing layer between parallel streams. *Journal of Fluid Mechanics* Vol. 123; 91-130.

[4] Raupach, M.R., Finnigan, J.J., Brunet, Y. (1996), Coherent eddies and turbulence in vegetation canopies: the mixing layer analogy. *Bound. Layer Meteorol*. 78, 351-382

[5] Lee X. (2000) Air motion within and above forest vegetation in non-ideal conditions. *Forest Ecology and Management* 135, 3-18

[6] Raupach, M.R., Thorn A.S., and Edwards, I. (1980), A wind tunnel study of turbulent flow close to regularly arrayed rough surfaces", *Bound. Layer Meteorol*. 18, 373-397.

[7] Bergstrom H. & Hogstrom U. (1989) Turbulent exchange above a pine forest. Part II. Organized Structures. *Boundary- Layer Meteorology* 49, 231- 263.

[8] Shabaka I.M.M.A., Mehta R.D. and Bradshaw P (1985), Longitudinal vortices imbedded in turbulent boundary layers. Part 1. Single vortex. *J. Fluid Mech.* 155, 37-57

[9] Gao W. Shaw R.H. & K.T. Paw (1989) Observation of organized structure in turbulent flow within and above a forest canopy. *Boundary-Layer Meteorology* 47, 349-377.

[10] Bruun H.H. (1995) *Hot Wire Anemometry*, Oxford University Press

[11] Farge M. (1992). Wavelet Transforms and their applications to Turbulence. *Annual Rev. Fluid Mechanics* 24, 395-457.

[12] Hudgins L., Friehe C. and Mayer M., (1993), Wavelet transforms and atmospheric turbulence. *Physical Review Letters* Vol.71, N. 20, 3279-3282.

[13] Raupach M.R., Finnigan J.J. and Brunet Y. (1989). Coherent eddies in vegetation canopies. *Proc. Fourth Australasian Conf. On Heat and Mass Transfer*, Christchurch, New Zealand 9-12 May. Pp. 75-90.

[14] Raupach M.R., Antonia R.A. and Rajagopalan S. (1991). Rough-wall turbulent boundary layers. *Appl. Mech. Rev*. Vol. 44, nº 1, pp. 1-25.